International Journal of Mechanical Sciences 53 (2011) 536–548

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Semi-analytical motion analysis of nano-steering devices, segmented piezotube scanners

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ARTICLE INFO

Article history:
Received 12 February 2011
Received in revised form
24 April 2011
Accepted 1 May 2011
Available online 19 May 2011

Keywords:
AFM
Piezotube scanners
GDQM
GDQEM
Nanomanipulation

ABSTRACT

Although the scanning probe microscopes (SPMs) and especially the atomic force microscope (AFM) are unrivaled devices for nanorobotic applications, their performance is hampered by some error sources, especially the scanner nonlinearities. For nonlinearities modeling and compensation, the present paper tries to introduce a new comprehensive viewpoint on the nonlinear behavior of the piezo scanners, especially the cylindrical ones. The static and free vibration analyses of the segmented piezotube scanners, presented using a semi-analytic approach, named the generalized differential quadrature method (GDQM), and some significant conclusions are achieved. Using a unique formulation for static solution, the negligibility of the cantilever mass and some manipulation forces are also proven. At the end, the effects of segmentation parameters are introduced and completely analyzed for the design optimization.

1. Introduction

The scanning probe microscopes (SPMs) and especially the atomic force microscope (AFM) were designated recently as nanorobots. Although these microscopes are unrivaled devices for nanorobotic applications, such as nanomanipulation, their performances are hampered by some error sources and scanner nonlinearities. The type of scanner used in the SPMs is the piezoscanner. They have various properties that make them different from the other scanner types; however, their accuracy is threatened by the nonlinear effect. The best way to overcome such a problem is to model and then compensate for the piezo-scanner's nonlinearity.

AFM manipulation does pose an interesting problem in robotics, however. An AFM tip can be used via different mechanisms to modify surfaces with nanometer resolution. Tasks such as pushing and pulling or cutting and indenting can be performed, and nanoscale objects can be mechanically moved with the AFM probe tip. The AFM tip can serve as a robotic hand to precisely position and assemble nano-objects via computer control.

There has been a great interest in exploring effective manipulation methods to build miniaturized systems, devices, structures, and machines in nanoscale. Sitti [1] surveyed the nanomanipulation systems and grouped nanomanipulation approaches according to their starting point, utilized process, operation type, manipulation environment, interaction type, etc. Because dimensional precision is crucial in nanomanipulation, attention to accuracy is essential in the process. Overall, more than 15 error sources exist in the AFM nanorobot operation. Although most of these errors are almost compensated for or corrected using advanced software, some error sources, generally termed nonlinearity effects, such as the scanner nonlinearities and ambient effects are the most challenging. Hitherto, as the scanner nonlinearities, for the mechanical view and hysteresis modeling of piezo actuators, the mass-spring-damper model has been considered [2]. Furthermore, the ambient effect is modeled in Ref. [3]. The present study introduces a new concept based on a completely distributed model for the implementation of nonlinearities in the future works. In the proposed shell dynamic analysis, a semi-analytical approach is used and thus, the calculation speed is maximized and the accuracy is guaranteed. The presented semi-analytical procedure is very important in the AFM system's case, because the piezotube of the AFM is considered as a cantilevered hollow cylinder, and for a cantilevered system, the exact solution does not exist.

Although, piezo tubes have not been completely analyzed for nanorobotic applications, some research works have been carried out for the analysis of general piezo laminated cylindrical shells. Also, the generalized differential quadrature method (GDQM) has been used in some works for mechanical analysis of systems. On the implementation of the GDQM in vibration problems, the boundary condition implementation is the most significant issue. Shu and Du [4,5] proposed the direct substitution of the boundary condition into discrete governing equations and the implementation of the general conditions. For the latter approach, the two physical conditions at a boundary point are discretized, if any, by the DQM. Then, one discrete condition is considered as the equation for the

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doi:10.1016/j.ijmecsci.2011.05.001